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FINAL TECHNICAL REPORT

Internal Waves and Mixing in the Aegean Sea

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Done with two Greek colleagues, Haris Kontoyiannias (Hellenic Centre for Marine Research) and Vassilis Zervakis (Univ. of the Aegean), the work on this grant was intended as a pilot project for an ONR DRI that did not occur because priorities shifted to the western Pacific. Before detailed planning began, the objectives were

1. To compare internal waves and mixing at shallow (100 m) and intermediate (500 m) depths,

2. To relate internal wave variability to changes in local winds, and

3. To observe how internal waves and mixing evolve between the basin and plateau, meaning the deep Cretan Sea and the Cyclidic Plateau.

To relate internal waves and mixing to bathymetry we needed a site previously mapped with a multibeam depth sounder. To obtain moored internal wave records of several months we needed a place with minimal fishing. Based on advice from Greek oceanograpers, in late August 2004 we set the moorings several miles west of Santorini.

Four moorings were set, three McLane Moored Profilers (MPs) and two ADCPs. The MPs traveled up and down the mooring wire at 0.25 m s^{-1}, measuring temperature, electrical conductivity, and velocity (Fig. 1). During intensive, ship-based measurements from R.V. Oceanus, we observed mixing along and across the bathymetry, repeating some lines to observed changes with time. A depth-cycling towed body was also used to examine the three-dimensional structure of some small water masses over the slope.

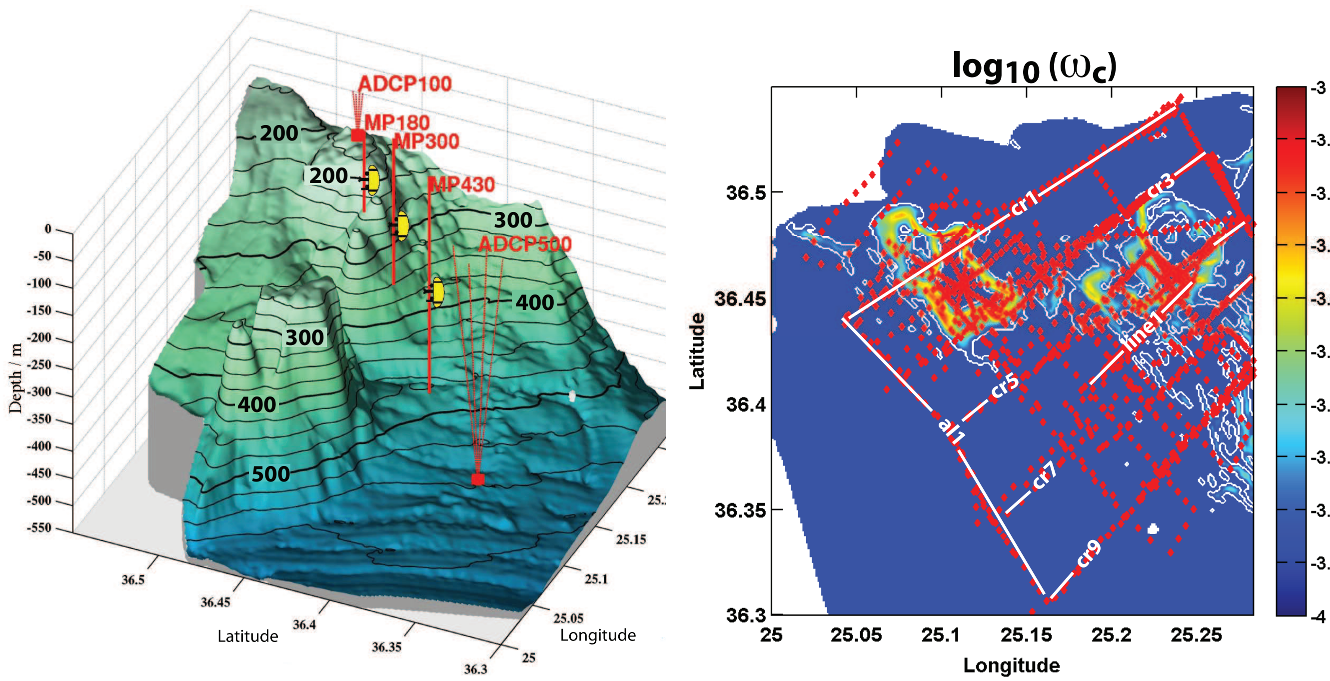

Figure 1: Left) Mooring locations, from shallow to deep: 300 kHz ADCP at 100 m; MP180, MP300, MP430, McLane Moored Profilers at 180, 300, and 430 m; ADCP500, 75 kHz ADCP at 500 m. The shallow end was on the Cycladic Plateau, and the deep end part way down the slope into the Cretan Sea. Right) Positions of microstructure profiles (red dots) over bathymetry displayed as logarithm (base 10) of the critical internal wave frequency of the bottom slope.

In 2004, summer weather over the eastern Mediterranean lasted late into the autumn, providing nearly flat seas and light winds when our intensive measurements began (Fig. 2). Except for one day, air temperatures were several degrees below sea surface temperatures, producing convection each night in the surface mixed layer. After almost a week, autumnal storms began, the last accompanied by a rapid drop in air temperature, further increasing convection and deepening the mixed layer to 60 m from 22 m when we started.

Stratification was a good approximation to two-layers, with $N^2 \approx 10^{-3}$ s^{-2} just below the mixed layer and rapidly falling to abyssal levels with increasing depth (Fig. 3. By 500 m, $N^2 = 2 \times 10^{-6}$ s^{-2}. Because open ocean dissipation rates, ϵ, are proportional to N^2, we found distinguishing noise from signal to be very difficult. As diapycnal diffusivity, $K_\rho = 0.2\epsilon/N^2$, is also inversely proportional to stratification, it was very important that we make this distinction carefully, not having had this as an issue before. The analysis took several years and is now being reviewed (*Gregg and Winkel*, 2009). When this paper is

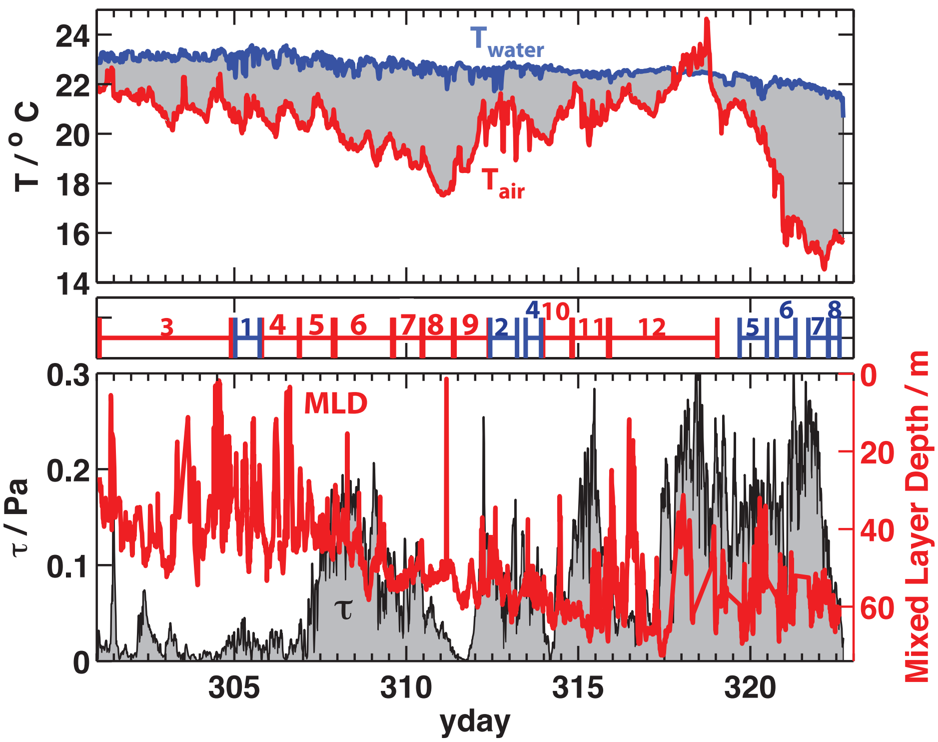

Figure 2: Meteorology during the intensive measurements. Upper) Sea surface and air temperatures. Middle) Times of AMP (red) and SWIMS (blue) groups. Lower) Mixed layer depth and wind stress, τ. Mixed layer depths indicate where density was 0.1 kg m^{-3} more than the shallowest value measured. Using 0.05 made little difference in most cases.

in press, we will finish two papers about the data and submit them to *Journal of Marine Systems*.

The importance of obtaining the best possible estimate of noise is shown in Figure 4, where ϵ is our best estimate and ϵ_{wn} is the average of the measured values. The best-estimate was made assuming the data were either signal or zero, i.e. there was no turbulence. Signals are categorized by magnitudes of $\epsilon/\nu N^2$ following the bands defined from laboratory experiments and numerical models by *Shih et al.* (2005). Below the pycnocline, the 5% of the data classified as strong contribute nearly at least 90% of ϵ.

The major surprise was the strong semi-diurnal internal tide (Fig. 5), unexected owing to the low barotropic tides in the Aegean, only a few centimeters in height and $\approx$ 2 cm/s in current magnitude. By contrast, magnitudes of the internal tide were ten times larger, 20 cm/s.

Below the pycnocline, mixing was closely confined near the bottom, whether on the sides of the two pinnacles or over the more gentle slope to the east. Levels increased significantly

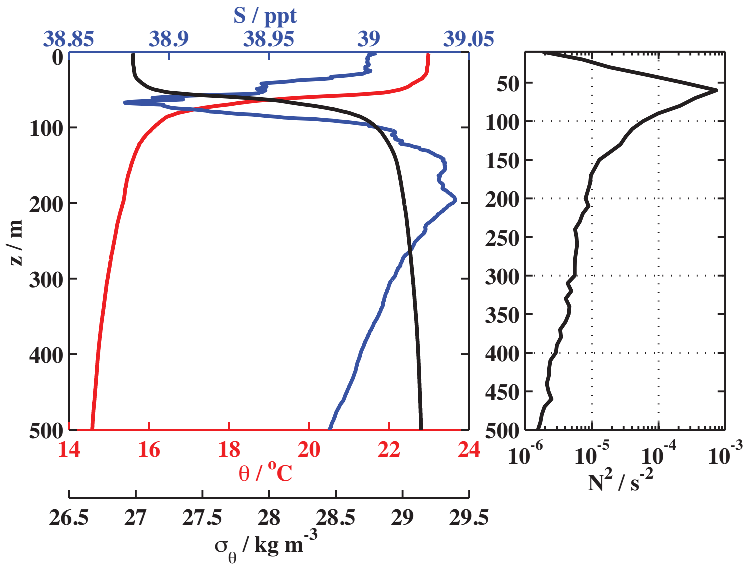

Figure 3: Typical profiles and stratification, obtained by averaging amp group 3 sub 10 along line al1, at the base of the slope.

during the measurements, presumably in response to the increased wind stress putting energy into the internal wave field.

Returning to the original objectives,

1. Shallow depths were mostly in the pycnocline and consequently have much larger dissipation rates than weakly stratified deep water, though this was not the case with diapycnal diffusivity, K_ρ.

2. Mixing increased with increases in wind stress accompanying the rapid transition from summer to autumnal weather.

3. Internal waves were dominated by the internal tide, apparently generated along the upper part of the slope. Closely confined near the bathymetry, detectable mixing was very weak and intermittent in deeper water.

When we are certain that our methods for separating noise from signal will be accepted, we will finish and submit *Alford et al.* (2010) and *Gregg et al.* (2010) to complete publication of these results.

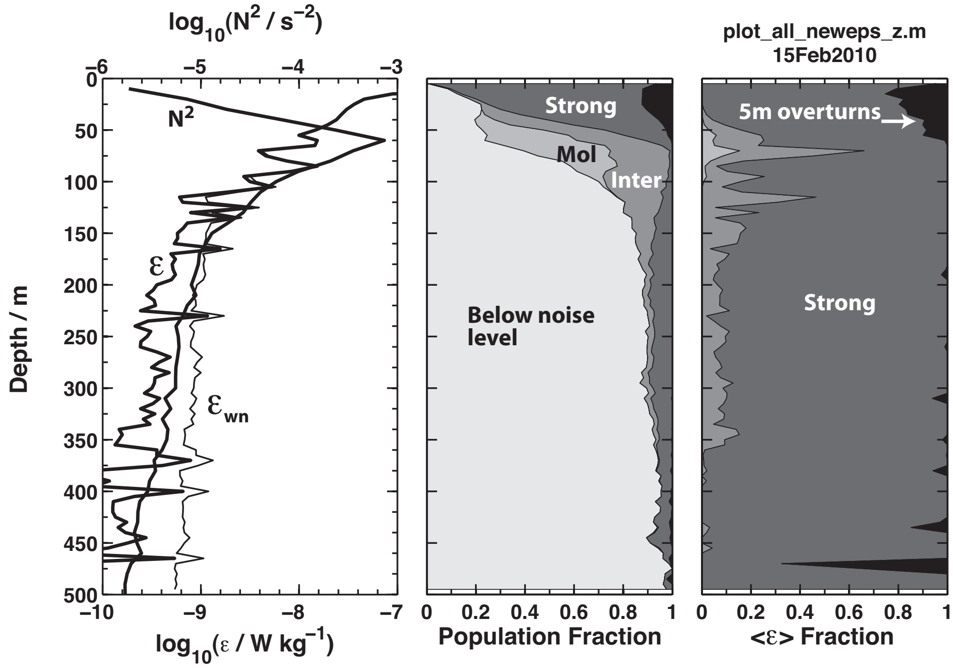

Figure 4: Averages of all dissipation data. Left) N^2 and average dissipation rate, ϵ, zeroing signals less than the noise level (thick) and setting them equal to the noise level, ϵ_{wn}. Middle) Distribution of observations by activity class. Most data are less than the noise level described earlier. Overturns larger than the 5 m data window were significant in the mixed layer and in weakly stratified water near the bottom. The other regimes follow the *Shih et al.* (2005) classification: *Mol* for molecular regime, $\epsilon/\nu N^2 < 7$; *Inter* for intermediate activity, and *Strong* for $100 < \epsilon/\nu N^2$. Right) Contributions the average dissipation profile, zeroing noisy signals.

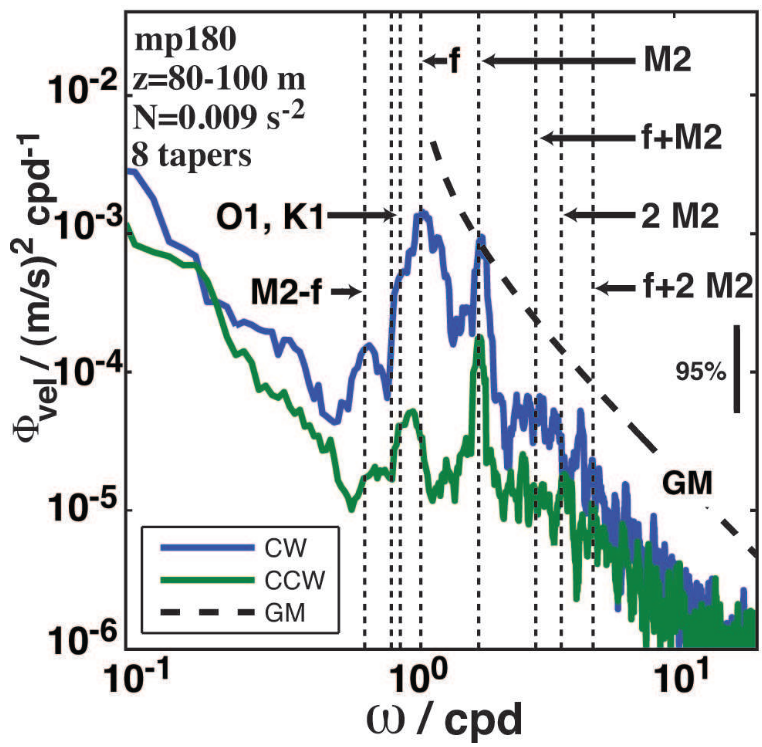

Figure 5: Velocity spectrum of MP180 averaged between 80 and 100 m. Strong peaks occur at inertial, f, and semi-diurnal, M_2, frequencies. The continuum is about 1/6 of the Garrett and Munk reference level.

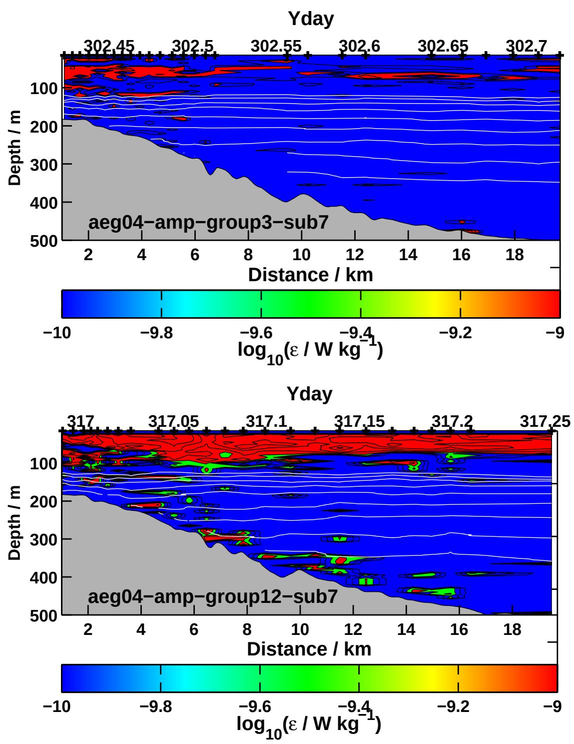

Figure 6: Dissipation across the slope on line cr4 before (AMP group 3, yday 302,6) and after (AMP group 12, yday 317.1) winds and convection increased.

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